A PRELIMINARY INVESTIGATION OF HANDLING QUALITIES REQUIREMENTS FOR HELICOPTER INSTRUMENT FLIGHT DURING DECELERATING APPROACH MANOEUVRES AND OVERSHOOT

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National Aeronautical Establishment

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A PRELIMINARY INVESTIGATION OF HANDLING QUALITIES REQUIREMENTS FOR HELICOPTER INSTRUMENT FLIGHT DURING DECELERATING APPROACH MANOEUVRES AND OVERSHOOT

ÉTUDE PRÉLIMINAIRE SUR LE PLAN DES CHARACTÉRISTIQUES ESSENTIELLES DE LA MANIABILITÉ DES HÉLICOPTÈRES POUR LES APPROCHES DÉCÉLÉRÉES ET POUR LE DÉPASSEMENT

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SUMMARY

A preliminary flight investigation was carried out to highlight deficiencies of helicopter handling qualities when performing low speed instrument approaches. Steep decelerating MLS approaches to a decision height of 50 feet, simultaneously decelerating to 20 knots, were performed in the NAE Airborne Simulator, a variable-stability Bell 205A helicopter.

Tracking performance, in terms of height, azimuth and speed errors was of an acceptable standard, but pilot workload was extremely high, especially during the overshoot phase. Benefits of different levels of control system augmentation were not readily apparent in this high workload environment.

In view of the results of this investigation, a follow-on program is proposed where further attempts will be made to determine the effects of display and control sophistication on pilot workload during slow-speed helicopter instrument procedures.

SOMMAIRE

On a procédé à des essais en vol préliminaires pour mettre en lumière les déficiences des hélicoptères sur le plan de la maniabilité lors d'approches exécutées aux instruments et à basse vitesse. Des approches MLS à décélération brutale jusqu'à 20 noeuds et jusqu'à une altitude de décision de 50 pieds ont été effectuées à l'aide du simulateur volant Bell 205A à stabilité variable de l'ÉAN.

Le maintien de la trajectoire en termes d'altitude, d'azimut et d'erreurs de vitesse était d'un standard acceptable mais la charge de travail du pilote s'est avérée extrêmement élevée, notamment pendant la phase de remise des gaz. Les avantages des différents niveaux d'augmentation de la sensibilité des commandes n'ont pas paru évidents dans ces conditions de pilotage particulièrement difficiles.

Compte tenu des résultats de ces essais, on propose la mise en oeuvre d'un programme en vue de déterminer les effets que la sophistication des affichages et des systèmes de commande pourraient avoir sur la charge de travail du pilote au cours d'approches exécutées aux instruments et à basse vitesse par des hélicoptères.

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A PRELIMINARY INVESTIGATION OF HANDLING QUALITIES REQUIREMENTS FOR HELICOPTER INSTRUMENT FLIGHT DURING DECELERATING APPROACH MANOEUVRES AND OVERSHOOT

1.0 INTRODUCTION

The Flight Research Laboratory (FRL) of the National Aeronautical Establishment (NAE) has been actively engaged in programs investigating the acceptability of helicopter IFR handling qualities. Most of this activity has been in a program jointly funded by the United States Federal Aviation Administration (FAA) and the NAE under Memorandum of Agreement AIA-CA-22 which was terminated in 1983. Data obtained was in support of the FAA's supplementary requirement published as Interim Standards for Helicopter IFR Certification. These requirements formed part of the "Rotorcraft Regulatory Review, Notice No. 1" as a prelude to incorporation of these standards within revised versions of Federal Airworthiness Regulations (FAR's) Parts 27 and 29. The results of these programs are published in References 1 and 2.

In February 1983 the FAA Rotorcraft Program Office prepared a Rotorcraft Master Plan (Reference 3) which addresses major aspects of rotorcraft requirements, including research and development, through the year 2000. A timetable for allowing helicopter all-weather operations to be incorporated into the U.S. National Airspace System (NAS) suggested three milestones; IFR Category II capability by the end of 1983, IFR Category IIIA capability with minimum IFR speed of 40 knots by mid-1990, and IFR Category IIIC capability with minimum IFR speeds of zero knots by mid-1995. At the same time the acceptance of the ICAO format TRSB Microwave Landing System will further enhance the operational capabilities of helicopter IFR flight. Canadian requirements should not differ greatly from those discussed above, and the acceptance of FAR standards by Transport Canada provides a common interest in the Rotorcraft Master Plan.

At the present time, weather minima and heliport design criteria for IFR are factors constrained profoundly by the inability to certify helicopters for IFR at low speeds for at least two reasons, the degradation of helicopter handling qualities characteristics at low speeds and the lack of a suitable presentation of low airspeeds to the pilot. Attempts are being made to address the latter to various degrees of success, but the low speed handling qualities requirements still remain relatively unexplored.

2.0 SCOPE OF THE PROGRAM

The experimental program described in this report was a preliminary investigation of low speed helicopter handling qualities in an attempt to identify particular deficiencies when performing and IFR decelerating approach to a low decision height/low airspeed followed by a visual landing or and instrument overshoot.

3.0 THE AIRBORNE SIMULATOR

The NAE Airborne Simulator is an extensively modified Bell 205A-1 helicopter with capabilities that have evolved over the last decade (Fig. 1). Basically, the standard hydraulically boosted mechanical control actuators have been replaced by dual-mode electro-hydraulic actuators. The actuator valves can be positioned mechanically from the left (safety pilot) seat or electrically from the right (evaluator pilot) seat full authority fly-by-wire station. Electrical controllers can be either conventional stick, pedals and collective through a programable force-feel system or 4-axis isometric force or deflection controllers. For this program, conventional controllers and the electro-mechanical servo valves were integrated with a variable force-feel system, a hybrid computing system and a set of motion sensors. The computing system consisted of three LSI 11/23 microprocessors, and D/A and A/D converters.

In order to improve the control responses of the teetering rotor system, the stabilizer bar has been removed. For this program, the longitudinal cyclic-to-elevator link, normally replaced with an electro-hydraulic actuator, was removed and the elevator was fixed in the neutral position.

In order to simulate instrument flight conditions visually an IMC Simulator manufactured by Instrument Flight Research Incorporated, Columbia, S.C. was employed. Goggles, worn by the evaluation pilot, had lenses which incorporated liquid crystals to vary the desired goggle opacity. For this program, a narrow field of view was maintained unobscured with the remaining peripheral view highly obscured. When descending through the decision height as selected by the evaluator on the radar altimeter, the peripheral view of the goggles could clear automatically to a simulated visibility of three miles. The safety pilot could inhibit the clearing of the goggles at decision height by activating a switch on his collective control when breakout to visual conditions was not desired.

4.0 COCKPIT DISPLAY

Primary approach/departure information was displayed on a Litton LED Multi-Mode Matrix display shown in Figure 2. The display philoscphy used during this program was to consolidate essential information in a raw situation form and display it in a manner to enhance cross check efficiency for approach, overshoot and departure tasks. Pitch and roll attitudes were presented conventionally. The left side of the display, functionally implying left hand control, was reserved for height presentation. Radar altitude, displayed digitally in the lower left window, flashed when at or below a decision height as selected with the radar altimeter index. MLS glideslope deviations were presented on the vertical scale on the left of the display, as a fixed scale and moving pointer for a full scale of $\pm 3^\circ$ glidepath. The right side of the display, functionally implying right hand control, was reserved for presentation of speed. Indicated airspeed was presented digitally in a window on the lower right of the display. Above this window, a vertical scale displayed either groundspeed error or airspeed error as selected by the pilot in increments of five knots to a maximum of 10 knots.

Paragraph 4.1 discusses the indicated airspeed and speed error presentations. MLS localizer deviations were displayed on a fixed horizontal scale at the bottom of the display with full deflection representing $\pm 9^\circ$.

Other information required for the approach/overshoot/departure tasks and not presented on the combined display was engine torque, heading, slip and skid, and sideslip. MLS reception was provided by a Co-Scan MLS receiver, selected by the safety pilot for a 6° glidepath on all approaches.

4.1 Speed Presentation

Dynamic pressure was obtained from two wide-angle pitot tubes located on two 10 inch booms on the nose of the aircraft. The static pressure source, which could swivel into the relative airflow, was located on the nose boom six feet from the aircraft nose. High frequency indicated airspeed excursions were smoothened with longitudinal inertial velocity to give smooth, accurate airspeed indications down to 15 knots.

Prior to descent on the 6° MLS glideslope, doppler groundspeed error was selected to be presented on the speed error indication discussed in Paragraph 4.0. Nulling this indication above 300 feet radar altitude allowed the pilot to track 60 knots groundspeed. This speed error presentation was programmed to command a groundspeed deceleration starting at 300 feet, and based on a groundspeed/radar altitude relationship, ending up at 10 feet radar altitude at zero groundspeed. A graphical presentation of the groundspeed/radar altitude relationship is shown in Figure 3. Nominally, this speed deceleration profile resulted in a constant pitch attitude ($\Delta\theta$ for deceleration approximately 6°), constant flight path deceleration of approximately 0.1G.

5.0 GROUND AIDS

A Co-Scan, fixed azimuth, variable glideslope MLS transmitter was located on NAE property, enabling the required airspace to be almost totally dedicated to the program with little interference from other airport traffic. A simulated but unmarked landing pad was located adjacent to and to the left of the MLS transmitter.

6.0 MODELLING

For this experiment, helicopter control system configurations covering a range of stability and control sophistication were provided to the evaluator to enable him to focus on aircraft handling deficiencies. The following configurations were used:

(a) Basic Bell 205A with rate damping augmentation in pitch, roll and yaw.

(b) Configuration (a) above with the addition of a heading hold feature when tail rotor pedals were placed within 1/4 inch of the trimmed neutral position.

(c) Rate command/attitude hold in pitch, roll and yaw with the basic Bell 205A collective control.

The variable control-force feel system was adjusted to provide 1/2 pound breakout force with a force gradient of 1/2 pound per inch in both pitch and roll cyclic control. Tail rotor pedal breakout and gradient were set at the minimum values required for positive self-centering. Electric trimming was provided for pitch, roll and yaw.

A description of the control system configurations is included as Appendix A.

7.0 EXPERIMENTAL PROCEDURES

It was assumed that in the final stages of the approach and the initial stages of the overshoot the pilot task would be primarily a "hands-on" control task with little auxiliary task activity required. All configurations were known to the pilot as he performed each task.

The evaluator was asked to perform a 6° MLS approach (Fig. 4) to a simulated heliport with a co-located MLS transmitter. Although some approaches were performed to a decision height of 100 feet AGL, the majority of approaches were performed to a decision height of 50 feet AGL. The evaluator set the required height on the radar altimeter index for two reasons:

(a) the radar altimeter index triggered the flashing of radar height on the combined display, and

(b) it also allowed the IMC goggles to clear on 50% of the approaches when not inhibited by the safety pilot.

On approach, with doppler groundspeed selected for the speed error display, maintaining a null on this display allowed the pilot to track 60 knots groundspeed down to 300 feet AGL, at which time the speed deceleration profile (Fig. 3) was activated automatically. At this point the evaluator lowered the collective and increased pitch attitude by 6° and tracked localizer, glideslope and speed error down to the decision height. The evaluator was not forewarned of the simulated weather conditions at decision height. At decision height the pilot was required to either come to a hover at the simulated heliport or overshoot into a missed approach procedure as dictated by the simulated weather conditions. The evaluator completed the questionnaires in Figures 5, 6, and 7, after each approach, landing or missed approach. Each questionnaire required the evaluator to submit a Cooper-Harper handling qualities rating (Fig. 8(a)) and a Certification-Related Assessment (Fig. 8(b)).

8.0 EVALUATIONS

Five test pilots participated in the evaluation flight testing, two certification test pilots from the FAA, one certification test pilot from Transport Canada and two research pilots from the NAE. A list of relevant pilot experience is shown in Figure 9. Each pilot flew approximately 4 hours training followed by 4 hours evaluation flying.

8.1 Weather Conditions During the Evaluations

Approach wind directions and velocities varied during the program; including 10 knots headwind in smooth conditions, 10 to 12 knots tailwind at ground level with windshear aloft and light to moderate convective turbulence, to conditions of a beam wind gusting from 15 to 22 knots with moderate turbulence and significant windshear.

8.2 Results of the Approach Assessments

The following summarizes the identification of the most difficult phase of the approach:

Phase	Number of Assessments
Prior to deceleration	4
During deceleration	49
No difference	5

Prior to the deceleration point and where the phase of flight made no difference to the assessment, the single most obvious deficiency noted was that of azimuth control. Location of the inclinometer was not within a convenient scan pattern and the evaluators were reluctant to use the sideslip angle presentation. A slight preference for the rate command/attitude hold with its sideslip washout feature was noted. Approaches where the most difficult phase was not necessarily during the deceleration were flown in conditions of significant turbulence and wind shear.

Azimuth control also appeared to dominate the pilot task during the deceleration. The tightening linear displacement gain of localizer display, increase in drift angle, and the inconvenient location of sideslip and heading presentations contributed to this high workload. Height control deficiencies were not as apparent as those for azimuth control, but served primarily as a distraction to the pilots azimuth and speed control. Of the three control parameters, speed control during the deceleration appeared to be the most easily accommodated in the available pilot workload. When approaching the decision height, increasing the pilot's radar altitude scan frequency practically saturated the workload situation of most pilots. The flashing of the radar altitude numerals and its display box was not an adequate warning of decision height. On a number of occasions pilots commenced overshoot just prior to reaching decision height. Although the maximum descent below a 50 foot decision height was approximately 15 feet, most pilots agreed that this could be reduced with an improvement in decision height warning.

8.3 Results of Landing Assessments

As can be noted in Figure 3, the programmed airspeed at 50 feet during deceleration was 22 knots. MLS coverage to full scale on the display at 50 feet was ±25 feet vertically and ±67 feet laterally. High on the glideslope and at too high a speed are errors most compromising to the success of the landing. Over this entire program, the maximum error conditions encountered at a 50 foot decision height, +10 feet and +18 knots, still allowed landings to be performed easily. Likewise, localizer errors up to maximum displacement at a decision height of 50 feet still allowed accurate landings to be performed easily. Histograms summarizing the evaluators' certification assessments and handling qualities ratings are included in Figure 10. Tracking performance is plotted in Figure 11 as "horizontal windows" for the 100 foot and 50 foot decision heights.

8.4 Overshoot

Although a combined display allowed the pilot to monitor three major parameters efficiently, this required a great deal of attention. During the final stages of the approach, the influx of radar altitude into the required pilots scan virtually saturated the workload situation. This fact, coupled with the psychological implications of descents to low decision heights caused four approaches to result in premature overshoots. Pilots' comments highlighted a requirement for better warning of decision height.

When a decision was made to overshoot, the pitch attitude of the aircraft was reduced and climb power was applied on the collective control. The dominant deficiency during this manoeuvre appeared to be in heading control. Pilots tended to prefer configurations where heading excursions were constrained by stability augmentation (rate command/attitude hold or collective decoupling) though ratings for all configurations are similar (Figure 12). In the absence of track guidance on overshoot the pilots did not have an accurate standard on which to base their performance.

9.0 CONCLUSIONS

It was evident from this program that decelerating IFR approaches could be performed with reasonable accuracy on a 6° glidepath to decision heights of 50 ft AGL and speeds allowing a landing on a helipad with a colocated MLS. However, an unacceptable level of pilot workload was required to do so. Deficiencies in displaying the required information to the pilot dominated the task to the extent that the effects of the stability and control characteristics of the different configurations on the acceptability of IFR handling qualities were not readily apparent.

The combined display of raw situation information could be greatly improved by:

(a) Inclusion of aircraft heading and sideslip on this display to reduce instrument crosscheck effort, and

(b) Provision of a better warning (audio) of decision height.

The workload demand on a pilot and his performance when overshooting from a low altitude/low airspeed situation are critical aspects in defining acceptable decision heights. Lack of overshoot track guidance during this program denied the evaluators an important performance standard on which to base their assessments. This aspect must be addressed in any future program.

10.0 FOLLOW-ON PROGRAM

A further program to investigate deficiencies in low altitude/low airspeed helicopter IFR approach characteristics is proposed. Briefly, the following will be addressed:

(a) Provision of raw situation data on a combined display will be improved,

(b) Flight director control laws for azimuth, glideslope and speed control will be developed and their usefulness in reducing workload and/or improving task performance will be assessed.

(c) Track guidance during the overshoot task will be provided by using a second MLS transmitter to simulator back-course operation.

(d) The Stability Augmentation System configuration featuring 3-axis rate damping with collective control decoupled from yaw, pitch and roll in this program will be retained and other configurations more closely representing presently certified CAT I helicopters will be included.

11.0 ACKNOWLEDGEMENTS

The authors are grateful to Mr. D.E. Sattler (NAE) for his participation in display programming, Mr. K.W. Davidson (NAE) in performing the safety pilot function for this program, and to the following individuals who provided their extensive certification expertise as evaluation pilots: Mr. J. Arnold (FAA), Mr. P. Balfe (FAA) and Mr. K. Mansfield (Transport Canada).

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5. Morgan, J.M. — *A Piloted Experiment in the Use of Multi Function Side-Arm Controllers in a Variable Stability Helicopter.* Ninth European Rotorcraft Forum, Stresa, Italy, September 1983.

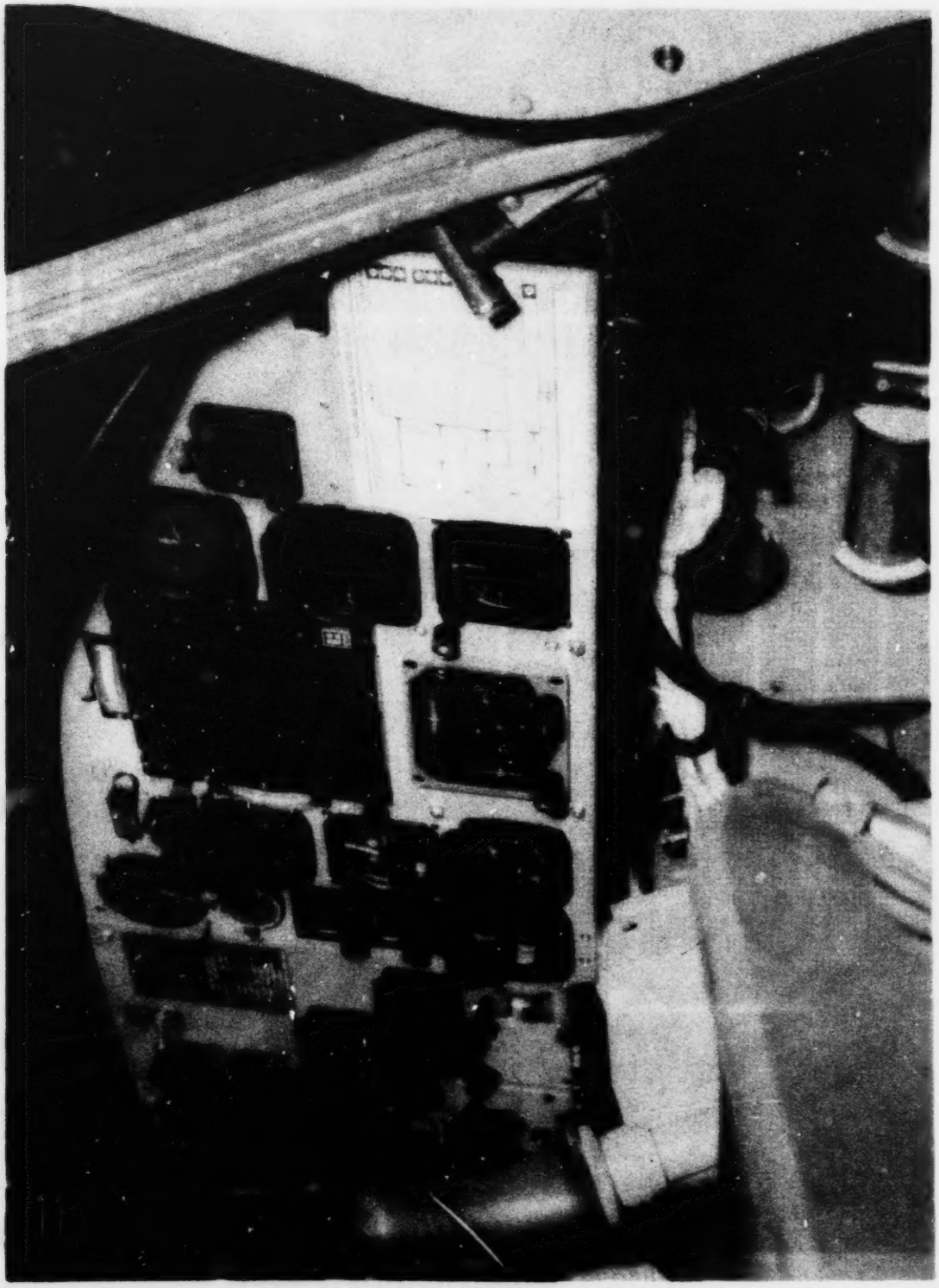


FIG. 1: AIRBORNE SIMULATOR EVALUATOR'S IFR COCKPIT

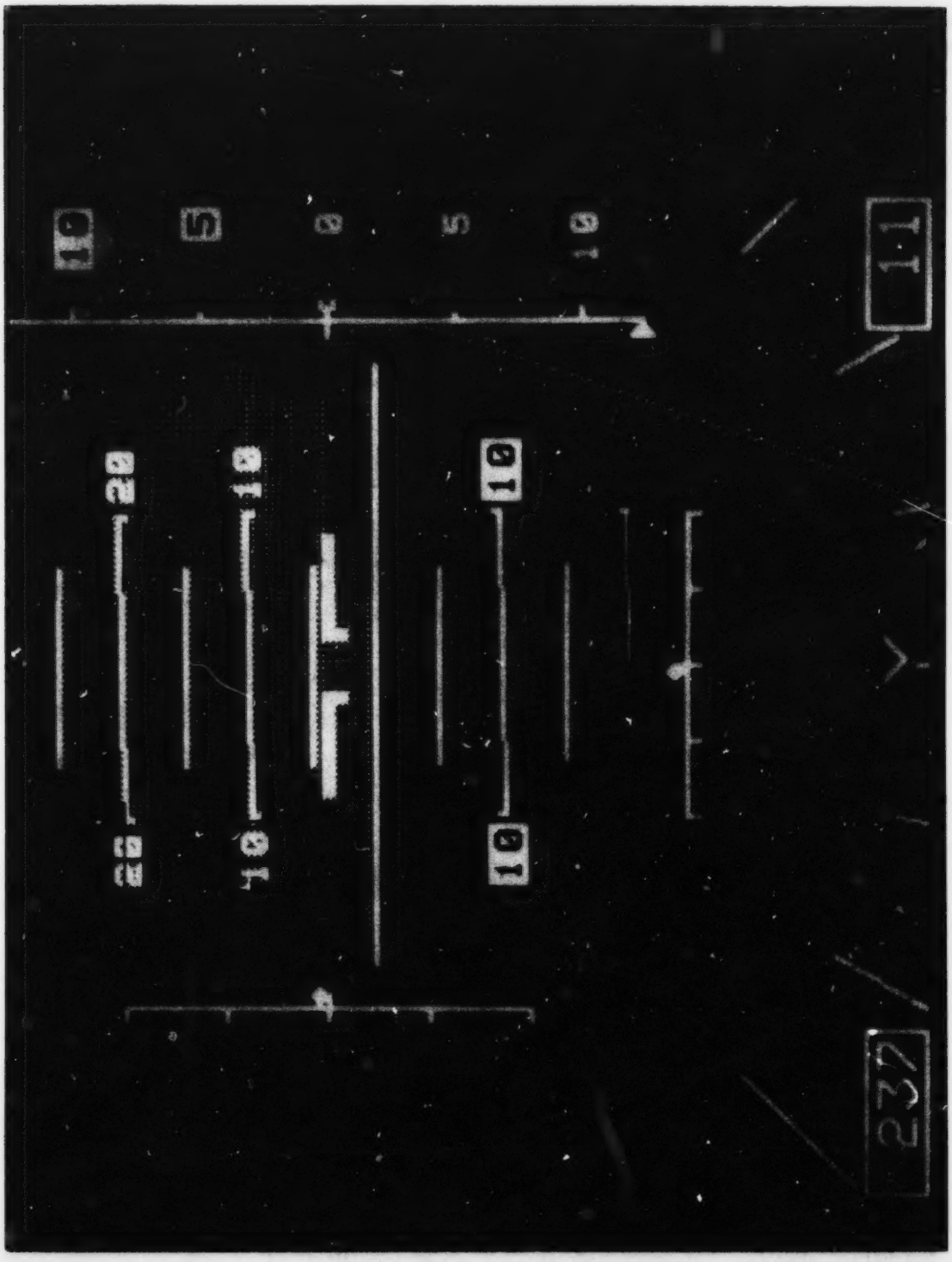
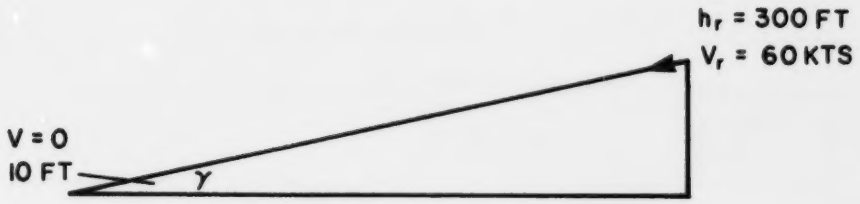


FIG. 2: LED MULTI-MODE MATRIX DISPLAY



$$V = \sqrt{V_r^2 - 2K(h_r - h)} \quad \text{WHERE } K = \frac{V_r^2}{2(h_r - 10)}$$

$$= V_r \sqrt{\frac{h-10}{h_r - 10}}$$

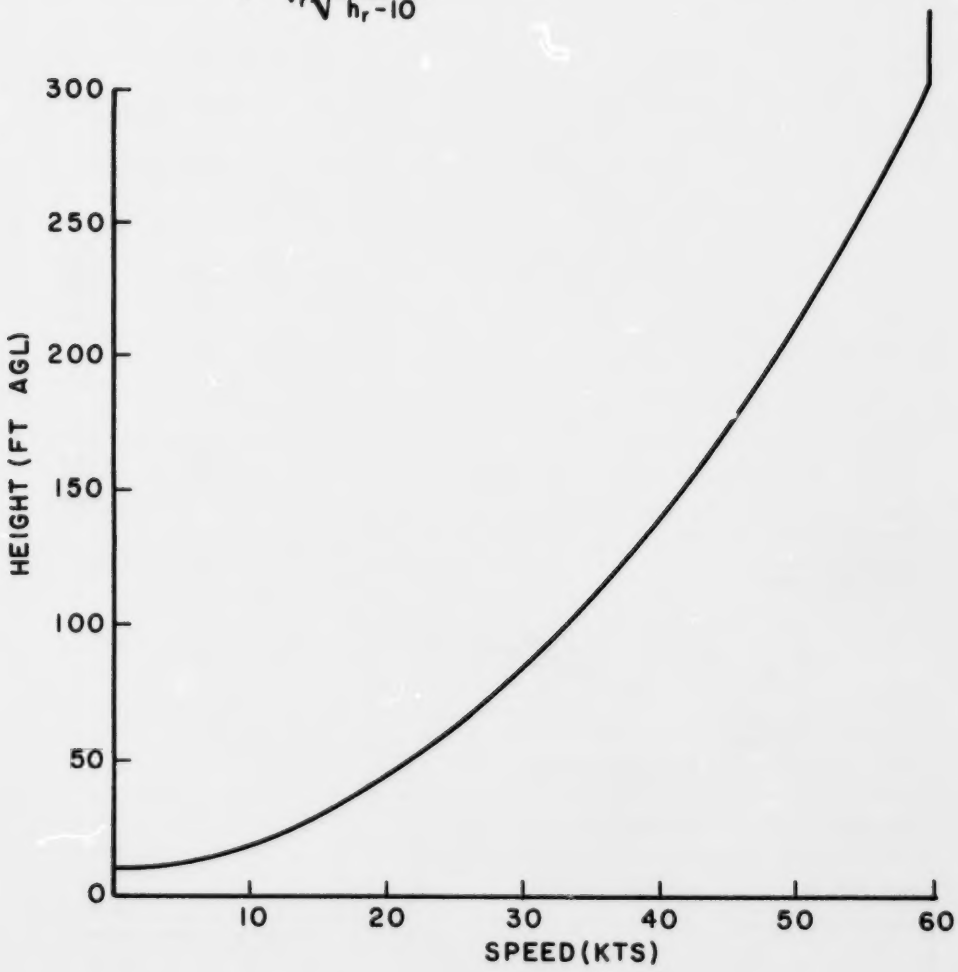


FIG. 3: SPEED DECELERATION PROFILE

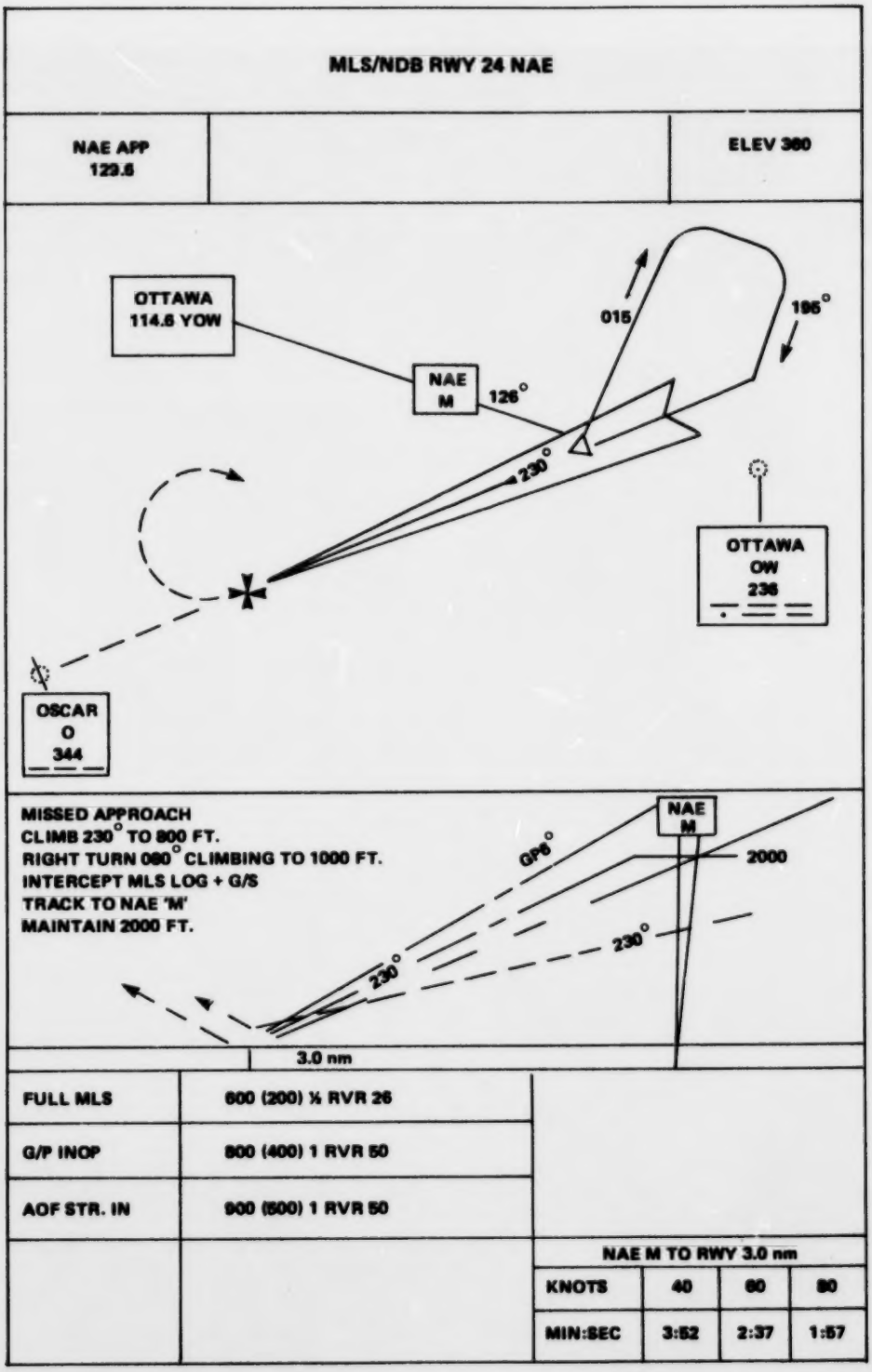


FIG. 4: MLS APPROACH PLATE

EVALUATION PILOT: _____ MODEL NO.: _____

FLIGHT NO. AND DATE: _____ RECORDER RUN NO.: _____

WINDS AND TURB.: _____ DECISION HEIGHT: _____

BREAKOUT: YES NO

---

1. a. Most difficult phase? _____

   b. Cooper-Harper rating

2. Comments on distinguishing characteristics or features:

   a. Prior to deceleration point:

      i. Azimuth Control

      ii. Elevation Control

      iii. Speed Control

      iv. General Comments

   b. During deceleration:

      i. Azimuth Control

      ii. Elevation Control

      iii. Speed Control

      iv. General Comments

3. IFR certification level (see extended description of categories):

   a. Good 1-Pilot

      Marginal 1-Pilot

      2-Pilot

      Non-certifiable

   b. Comments:

FIG. 5: APPROACH QUESTIONNAIRE

1. a. Most difficult phase? _____

   b. Cooper-Harper rating

2. Comments on distinguishing characteristics or features:

   a. Prior to MLS Intercept:

      i. Heading Control

      ii. Speed Control

      iii. Other Features or General Comments:

   b. After MLS Intercept:

      i. Azimuth Tracking

      ii. Elevation Tracking

      iii. Speed Control

      iv. Other Features or Comments:

3. IFR certification level (see extended description of categories):

   a. Good 1-Pilot

      Marginal 1-Pilot

      2-Pilot

      Non-certifiable

   b. Comments:

FIG. 6: MISSED APPROACH QUESTIONNAIRE

1. Breakout Height? _____

2. Cooper-Harper rating

3. Comment on the following:

   a. Deceleration rate to touchdown

   b. Flight path tracking

   c. Accuracy of touchdown

   d. General Comments:

FIG. 7: LANDING QUESTIONNAIRE (VFR)

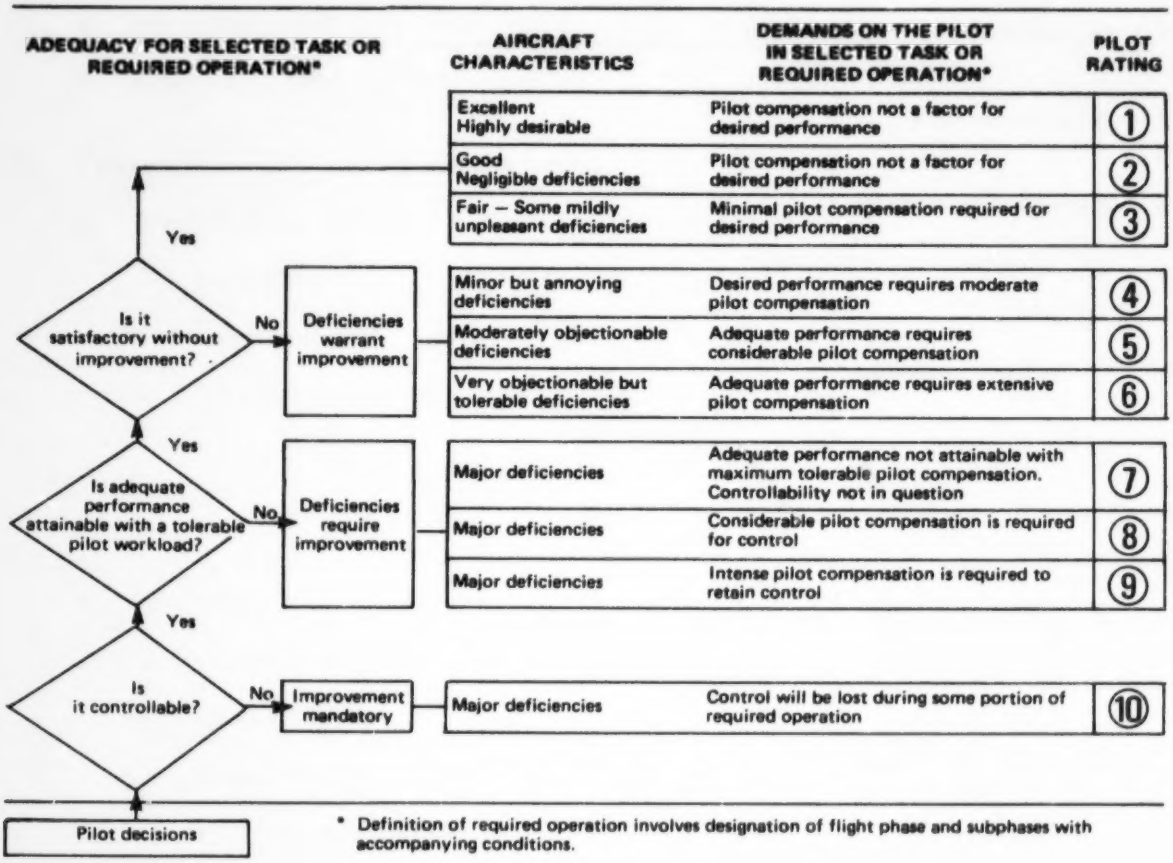

ADEQUACY FOR SELECTED TASK OR REQUIRED OPERATION*
AIRCRAFT CHARACTERISTICS
DEMANDS ON THE PILOT IN SELECTED TASK OR REQUIRED OPERATION*
PILOT RATING
Excellent Highly desirable
Pilot compensation not a factor for desired performance
1
Good Negligible deficiencies
Pilot compensation not a factor for desired performance
2
Fair – Some mildly unpleasant deficiencies
Minimal pilot compensation required for desired performance
3
Yes
Is it satisfactory without improvement?
No
Deficiencies warrant improvement
Minor but annoying deficiencies
Desired performance requires moderate pilot compensation
4
Moderately objectionable deficiencies
Adequate performance requires considerable pilot compensation
5
Very objectionable but tolerable deficiencies
Adequate performance requires extensive pilot compensation
6
Yes
Is adequate performance attainable with a tolerable pilot workload?
No
Deficiencies require improvement
Major deficiencies
Adequate performance not attainable with maximum tolerable pilot compensation. Controllability not in question
7
Major deficiencies
Considerable pilot compensation is required for control
8
Major deficiencies
Intense pilot compensation is required to retain control
9
Yes
Is it controllable?
No
Improvement mandatory
Major deficiencies
Control will be lost during some portion of required operation
10
Pilot decisions
* Definition of required operation involves designation of flight phase and subphases with accompanying conditions.

FIG. 8(a): HANDLING QUALITIES RATING SCALE

BASED ON YOUR SHORT EVALUATION, IN WHICH OF THE FOLLOWING CATEGORIES WOULD YOU PLACE THIS CONFIGURATION:

1. The helicopter has good flying qualities and could be operated safely in a high-density IFR environment by one pilot without the assistance of additional crew members. ☐

2. The helicopter has marginal flying qualities for operations in a high-density IFR environment by one pilot without the assistance of additional crew members. ☐

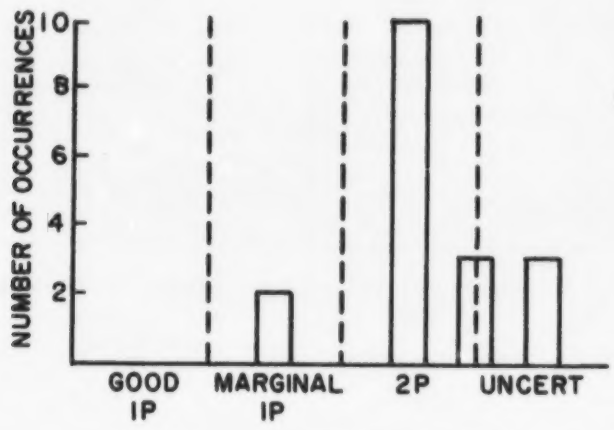
3. The helicopter has flying qualities deficiencies which make it unsuitable for single-pilot operations in a high-density IFR environment, however it could be operated safely within such an environment if the pilot-in-command were relieved of all non-control tasks by an additional qualified crew member. ☐

4. The helicopter has major flying qualities deficiencies which make it unsuitable for operation within a high-density IFR environment. ☐

FIG. 8(b): CERTIFICATION RELATED ASSESSMENT

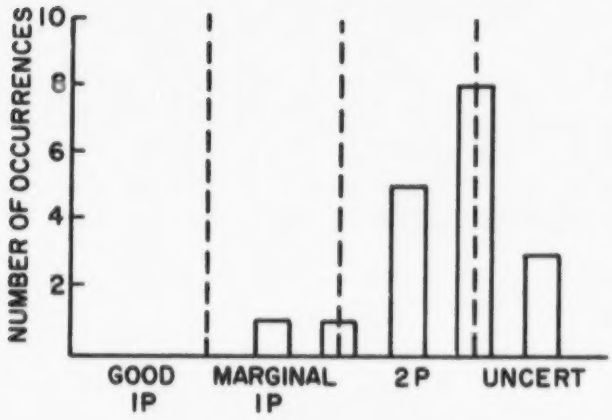
PILOT	TOTAL FLIGHT TIME	TOTAL HELICOPTER TIME	TOTAL INSTRUMENT TIME
A	8600	5350	1025
B	4000	1000	300
C	3200	2000	500
D	6600	950	490
E	7800	1100	1000

FIG. 9: SUMMARY OF EVALUATORS' FLIGHT EXPERIENCE



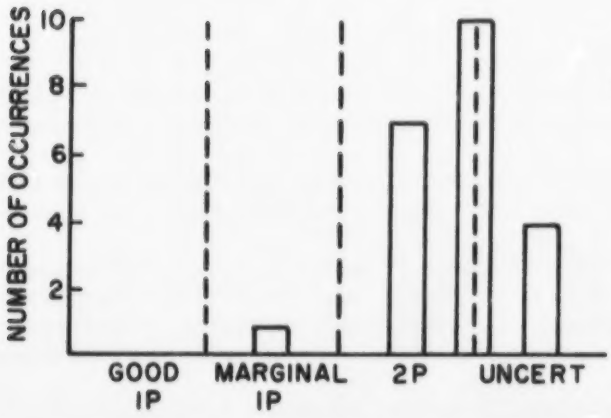
AVERAGE C/H RATING 5.4

(a) RATE COMMAND – ATTITUDE HOLD



AVERAGE C/H RATING 5.8

(b) 3-AXIS RATE DAMPED + DECOUPLED COLLECTIVE



AVERAGE C/H RATING 5.7

(c) 3-AXIS RATE DAMPED

FIG. 10: SUMMARY OF CERTIFICATION ASSESSMENTS DECELERATING APPROACH TO 50 FT HEIGHT

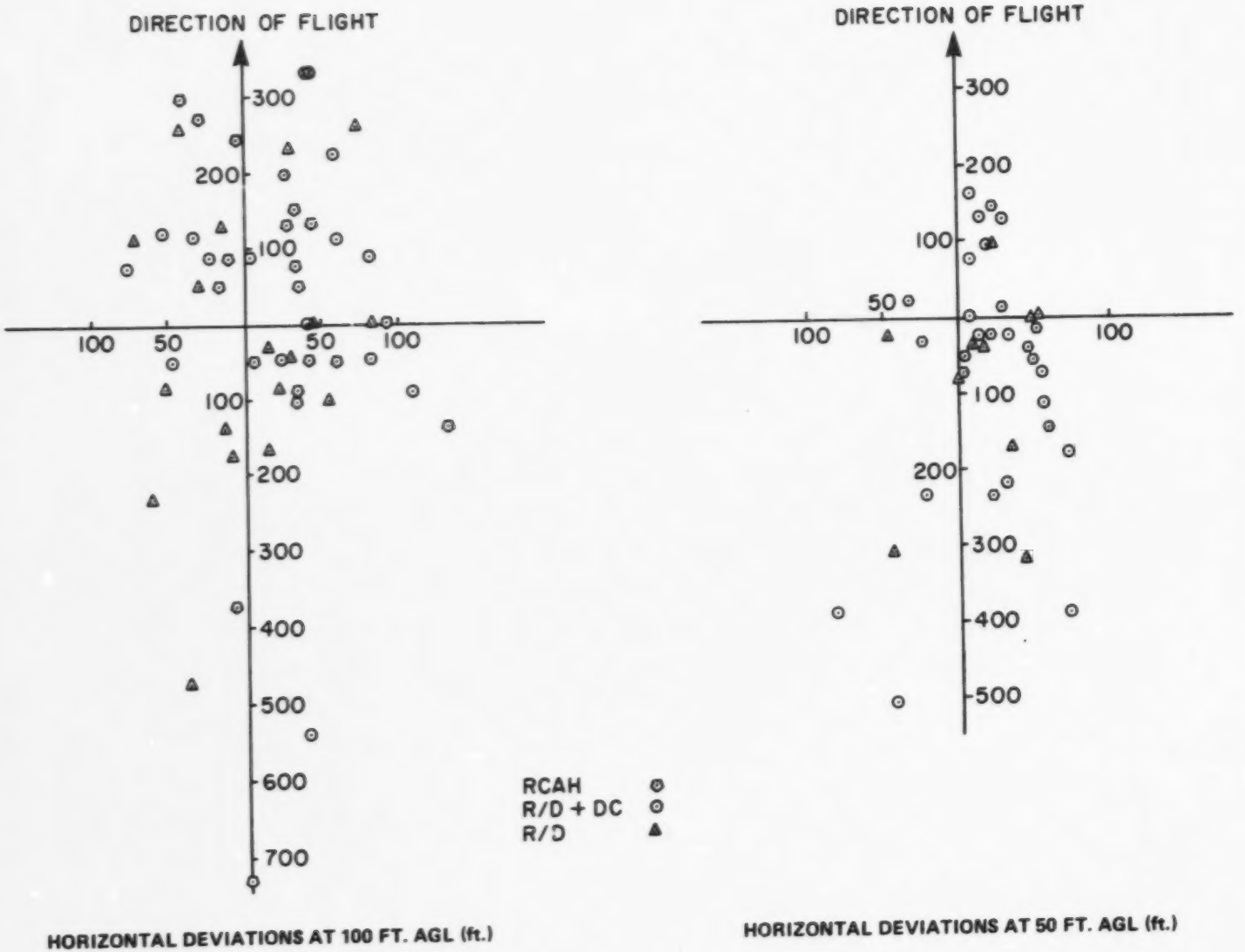
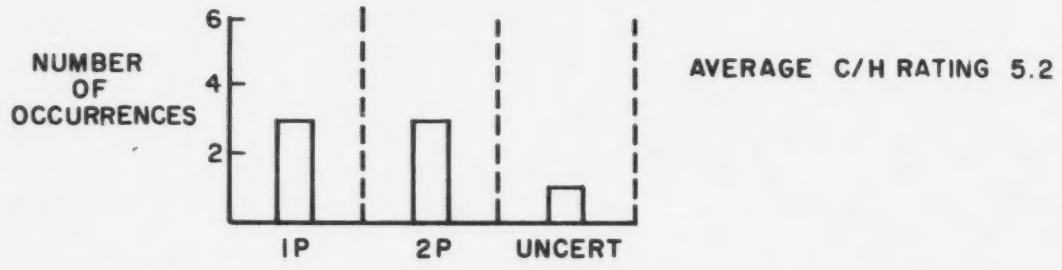
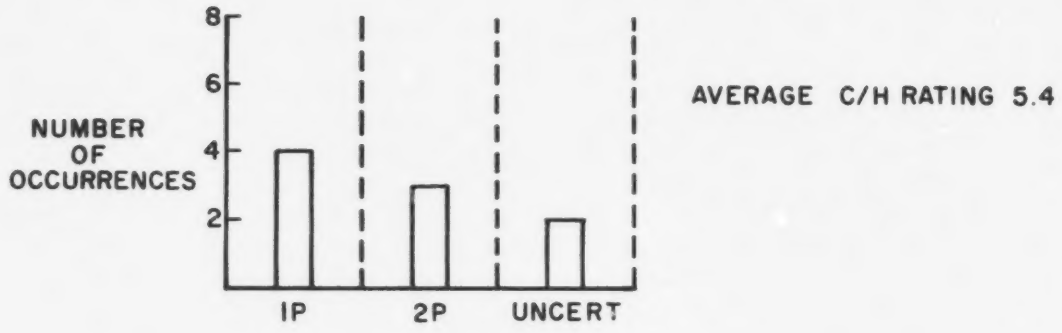


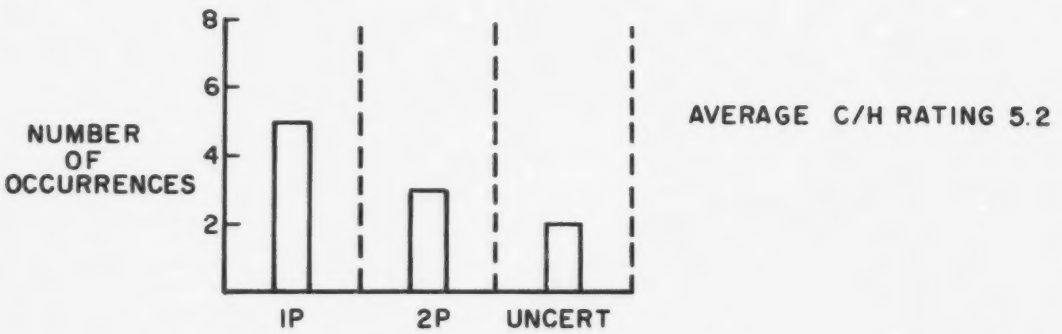
FIG. 11: HORIZONTAL FLIGHT PATH DEVIATIONS AT 100 AND 50 FEET



(a) RATE COMMAND – ATTITUDE HOLD



(b) 3-AXIS RATE DAMPED + DECOUPLED COLLECTIVE



(c) 3-AXIS RATED DAMPED

FIG. 12: SUMMARY OF CERTIFICATION ASSESSMENTS OVERSHOOT FROM DECELERATING APPROACH – 50 FT HEIGHT

APPENDIX A

CONTROL SYSTEMS DESCRIPTION

Symbology

δ_a	drive to roll channel
δ_e	drive to pitch channel
δ_r	drive to yaw channel
ϵ	error
ϕ	roll attitude
θ	pitch attitude
p	roll rate
q	pitch rate
r	yaw rate
β_i	inertial side-slip = Tan^{-1} (v/u)
C	actuator conversion coefficient
G	gain
K	gain
L_{p_m}	roll damping (model)
M_{q_m}	pitch damping (model)
N_{r_m}	yaw damping (model)
$L_{\delta a_m}$	roll control power (model)
$M_{\delta e_m}$	pitch control power (model)
$N_{\delta r_m}$	yaw control power (model)

Subscripts

a	roll channel
e	pitch channel
y	yaw channel
b	basic
i	incremental

Subscripts (Cont'd)

mix	complementary mixed quantity
p	due to pilot's input
r	due to yaw rate
c	commanded
tc	turn co-ordination
dc	de-coupling

INTRODUCTION

The control system types used for this experiment can be classed generically as primitive and advanced. Although both system types contain feedback loops, the primitive system loop gains are so low that the pilot's input dominates at all times, while the advanced system gains are sufficiently high to make the pilot's command simply another input to the closed loop system. Using the primitive system, prolonged unattended flight is not possible, while with the advanced system it is. The terms above can only be applied to roll, pitch and yaw, since throughout the project collective control was completely open loop.

PRIMITIVE SYSTEMS

General

Figure A-1 shows a typical control channel for these types of system. Three levels of pilot assistance are provided, all of which can be controlled from the cockpit in flight by means of the switches shown. This gives four possible configurations, since with all switches off the pilot is flying the aircraft directly, and it should be remembered that this is direct control of a Bell 205A with the usual stabilizer bar removed. In this case the pilot's input feeds the roll actuator drive directly via Ca, a coefficient which converts the internal computer full scale signal to a level which matches the actuator electrical drive requirements. Similar coefficients are used in all four drive channels.

Stabilizer Bar

The stabilizer bar model, considered the first level of stability augmentation was derived from data in Reference 4, and consists of a gained low-pass filter with a break-point at 0.33 rad/sec. Filter input is roll or pitch rate and the output is swash-plate angle. It is identical in pitch and roll. This may be written as:

$$\delta_a = \delta_{a_p} - p\left(\frac{0.5356}{s + 0.33}\right)$$

and

$$\delta_e = \delta_{e_p} - q\left(\frac{0.5356}{s + 0.33}\right)$$

ADVANCED CONTROL SYSTEMS

General

For this program only one form of advanced control system was used. Rate Command/ Attitude Hold (RCAH), though the implementation of such a system in yaw required some additional complexity. This is because a yaw rate-command system is not the ideal from a piloting point of view in forward flight, where side-slip rather than yaw rate is the parameter of most interest to the pilot. For this reason that channel undergoes a blended mode change from a Rate Command/Heading Hold at and around the hover, to a Beta Command system in forward flight.

Rate Feedback Loops

Past experience with the Airborne Simulator has shown that the control response lags inherent in the host vehicle seriously limit the open loop gains that can be used in simple loop closure therefore, to achieve the gains required for good closed-loop performance, a somewhat more subtle approach must be used. While several methods have been used to alleviate this effect, including the use of rate derivative (angular acceleration) loops to 'equalize' the system, (as reported in Ref. 2) the present method of high frequency modelling appears to be the most effective. As can be seen in Figures A-2, A-3 or A-4, the rate feedback parameter is a composite or mixed value, derived from a low passed aircraft rate summed with the output from a simple lag free linear model of the aircraft at high frequency.

The latter is implemented by taking a high passed signal from the final drive and feeding this to a first order model of the basic 205. The model parameters are themselves functions of the aircraft forward speed. The break-point for the complementary filters for these processes was set at 1.5 Hz for all three channels.

Roll and Pitch System

There is great similarity between the RCAH systems in Roll and Pitch as can be seen from Figures A-2 or A-3. The pilot's command is integrated to form an attitude command (modified with roll angle in the pitch channel). These two signals are differenced with their respective feedback parameters, producing error signals which are then gained and fed to the aircraft actuators. In both channels a delta attitude term, based on an inertially derived beta is provided to decouple the effects of the Euler transform of yaw excursions into these axes when the aircraft is at extreme attitudes. The use of beta in place of the more correct integral of rate error was simpler to achieve and has proved very successful. The pitch channel has one additional term, a command augmentation term to provide steady state turn co-ordination, relieving the pilot of the necessity of 'pulling' the aircraft around a turn which would be required if this term was not present.

Rate Damping Augmentation

The next level of sophistication in the primitive systems is augmented rate damping in pitch, roll and yaw. It was desired to keep an approximately constant value for the augmented damping of the aircraft over the entire speed range, which was achieved by use of a speed derived scheduling function of the form:

$$G = G_b + F(u) * G_i$$

where

$$F(u) = (100.0 - u)/70.0$$

such that

$$1.0 >= F(u) >= 0.0$$

That is, a function whose value is 1.0 below 30 kt TAS reducing linearly to zero at 100 kt TAS. This function, together with values of G_b and G_i for the three channels again selected on the basis of Reference 4, gives approximate values for the augmented damping parameter of -1.5/sec in all three channels. The rate damping implementation may be expressed as:

$$\delta_a = \delta_{a_p} - p(G_{a_b} + F(u)\, G_{a_i})$$

$$\delta_e = \delta_{e_p} - q(G_{e_b} + F(u)\, G_{e_i})$$

$$\delta_r = \delta_{r_p} - r(G_{y_b} + F(u)\, G_{y_i})$$

Collective De-Coupling

Reference 4 was also the source of data for the collective de-coupling term which is the final level of pilot assistance provided in the primitive systems. Empirical curve fitting of data on the cross-coupling terms suggested a second order match was adequate in all three channels (Roll, Pitch and Yaw) provided different zero speed offsets were used. The term is of the form:

$$\delta_{\delta_c} = (k_1 + k_2 u + k_e u^2) * \delta_c$$

Yaw Channel

The yaw channel is structurally different from those for roll and pitch due to the requirements to change from Beta to heading hold modes with speed changers and the very different natural characteristics of the basic aircraft in yaw. Instead of producing error signals and gaining them as a command signal, each input to the initial summing junction is independently gained before summation. These gains in the case of yaw rate and sideslip are modified by a blending function and its inverse. Each leg contains a gain that is the output of a slow first order low pass filter, the input to which is switched between 1.0 and 0.0 as the aircraft passes through 40 kt. At speeds below 40, the beta term is completely suppressed and the yaw rate term augmented to give a crisp rate command system, while above 40 kt the yaw rate term is diminished to a level where it serves only as a damping term in the beta dominated loop. Also at low speed, an integral of the rate error term is activated to provide a pseudo heading-hold function. This channel is also provided with a turn co-ordination term, while there is a forward feed of collective de-coupling to reduce the demands on the closed loop system to counteract the large moments produced by collective in yaw.

Equations

The algorithms for the advanced control systems are

Pitch and Roll

$$\left.\begin{aligned} \theta_{c_{dc}} &= \beta_i \ \mathrm{Sin}\,\phi \cos\theta \\ \phi_{c_{dc}} &= \beta_i \ \frac{\mathrm{Cos}\,\phi \ \mathrm{Sin}\,\theta}{\mathrm{Cos}\,\theta} \end{aligned}\right\} \quad \text{yaw channel de-coupling}$$

Pitch and Roll (Cont'd)

$$r_{tc} = g/u \ \text{Sin}\,\phi \ \text{Cos}\,\theta$$

$$q_{tc} = g/u \ \frac{\text{Sin}^2\,\phi \ \text{Cos}\,\theta}{\text{Cos}\,\phi}$$

} turn co-ordination

$$\phi_{c_p} = \int p_c \, dt$$

$$\theta_{c_p} = \int q_c \ \text{Cos}\,\phi \, dt$$

} develop attitude commands

$$\epsilon_p = p_c - p_{mix}$$

$$\epsilon_q = q_c + q_{tc} - q_{mix}$$

$$\epsilon_\phi = \phi_{c_p} + \phi_{c_{dc}} - \phi$$

$$\epsilon_\theta = \theta_c + \theta_{c_{dc}} - \theta$$

} error signals

$$\delta_a = G1_\phi \, \epsilon_p + G2_\phi \, \epsilon_\phi$$

$$\delta_e = G1_\theta \, \epsilon_q + G2_\theta \, \epsilon_\theta$$

} final drive

Yaw

$$K_B = K \ \frac{0.5}{s + 0.5}$$

$$K_{B_i} = 1 - K_B$$

} blending function

IF: (TAS $\geq$ 40 kt) THEN: K = 1.0
ELSE: K = 0.0

$$\delta_{r_r} = r_{mix} \ [G3_y + G3_{y_i} K_{B_i}] \qquad \text{rate term}$$

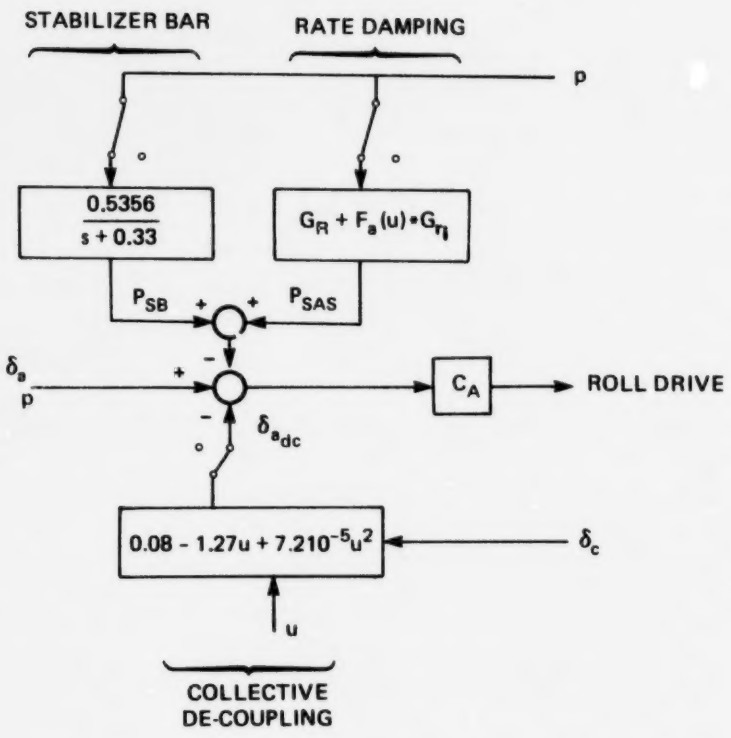
$$\delta_{r_\beta} = \beta_i \, \Delta N_v * K_B \qquad \text{sideslip term}$$

$$r_c = \delta_{r_p} \, G1_y \qquad \text{pilot term}$$

$$\epsilon_r = r_c + \delta_{r_\beta} - \delta_{r_r} \qquad \text{rate error}$$

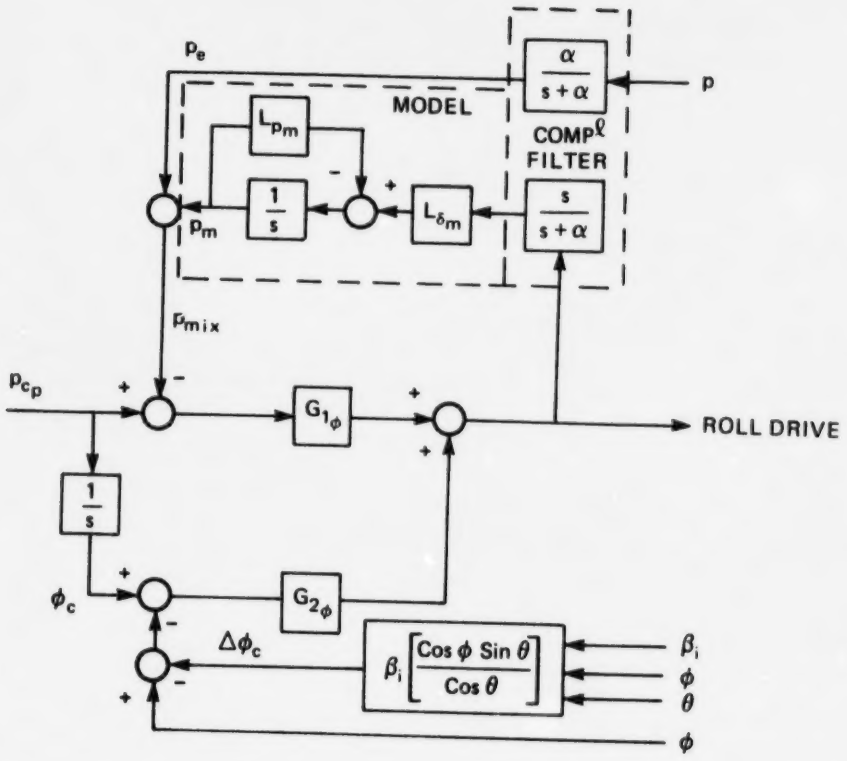
$$\delta_{r_i} = \epsilon_r + \int \epsilon_r \, K_{B_i} \, dt \qquad \text{total error}$$

$$\delta_{r_f} = \delta_{N_i} \ [C_{r_b} + F(u) \, C_{r_i}] - \delta_{r_{\delta_c}} \qquad \text{final drive}$$



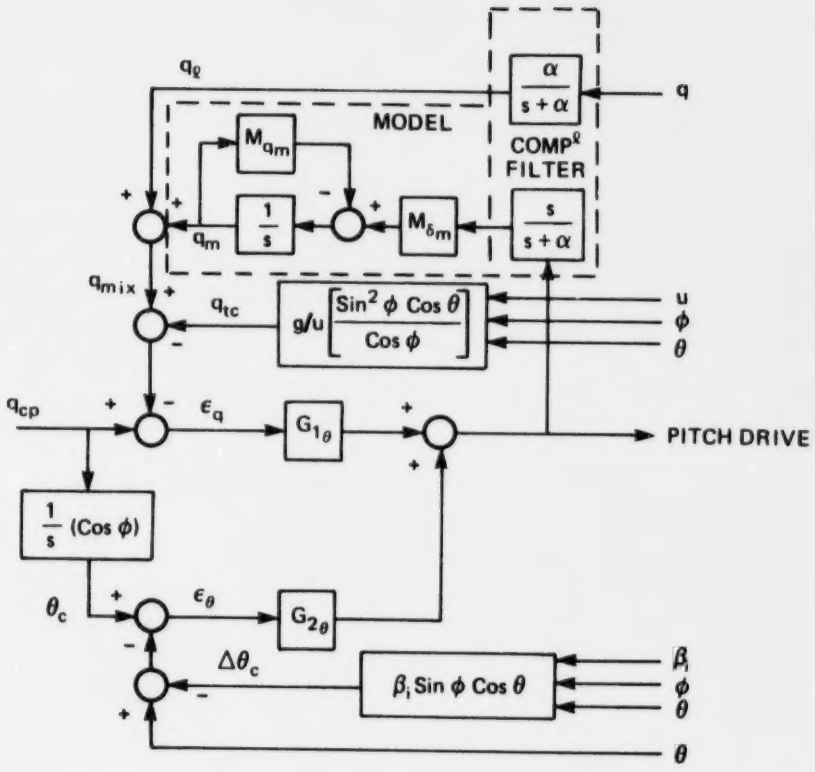
MHIFR7: PRIMITIVE SYSTEM – ROLL CHANNEL

FIG. A-1



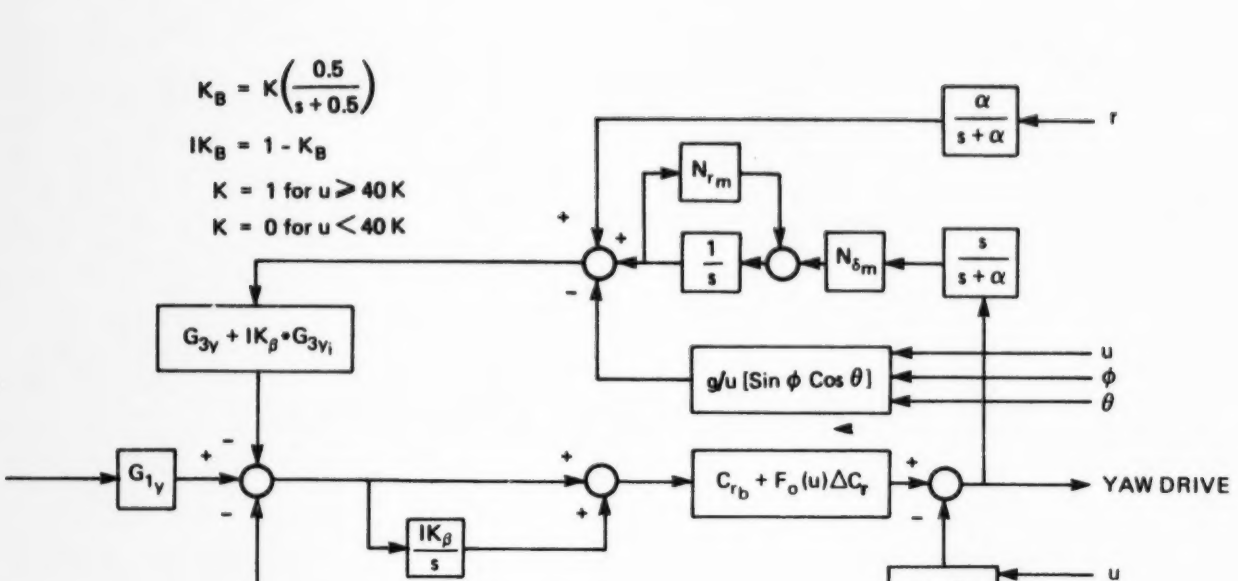
MHIFR7: RCAH – ROLL CHANNEL

FIG. A-2



MHIFR7: RCAH – PITCH CHANNEL

FIG. A-3



MHIFR7: RCAH – YAW CHANNEL

FIG. A-4

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NOTES (13)

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1. Helicopters — handling
2. Helicopters — instrumentation
3. Instrument landings
4. Flight testing

SUMMARY/SOMMAIRE (15)

A preliminary flight investigation was carried out to highlight deficiencies of helicopters handling qualities when performing low speed instrument approaches. Steep decelerating MLS approaches to a decision height of 50 feet, simultaneously decelerating to 20 knots, were performed in the NAE Airborne Simulator, a variable-stability Bell 205A helicopter.

Tracking performance, in terms of height, azimuth and speed errors was of an acceptable standard, but pilot workload was extremely high, especially during the overshoot phase. Benefits of different levels of control system augmentation were not readily apparent in this high workload environment.

In view of the results of this investigation, a follow-on program is proposed where further attempts will be made to determine the effects of display and control sophistication on pilot workload during slow-speed helicopter instrument procedures.